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# Evaluating radiation-induced noise effects on pixelated sensors for the National Ignition Facility

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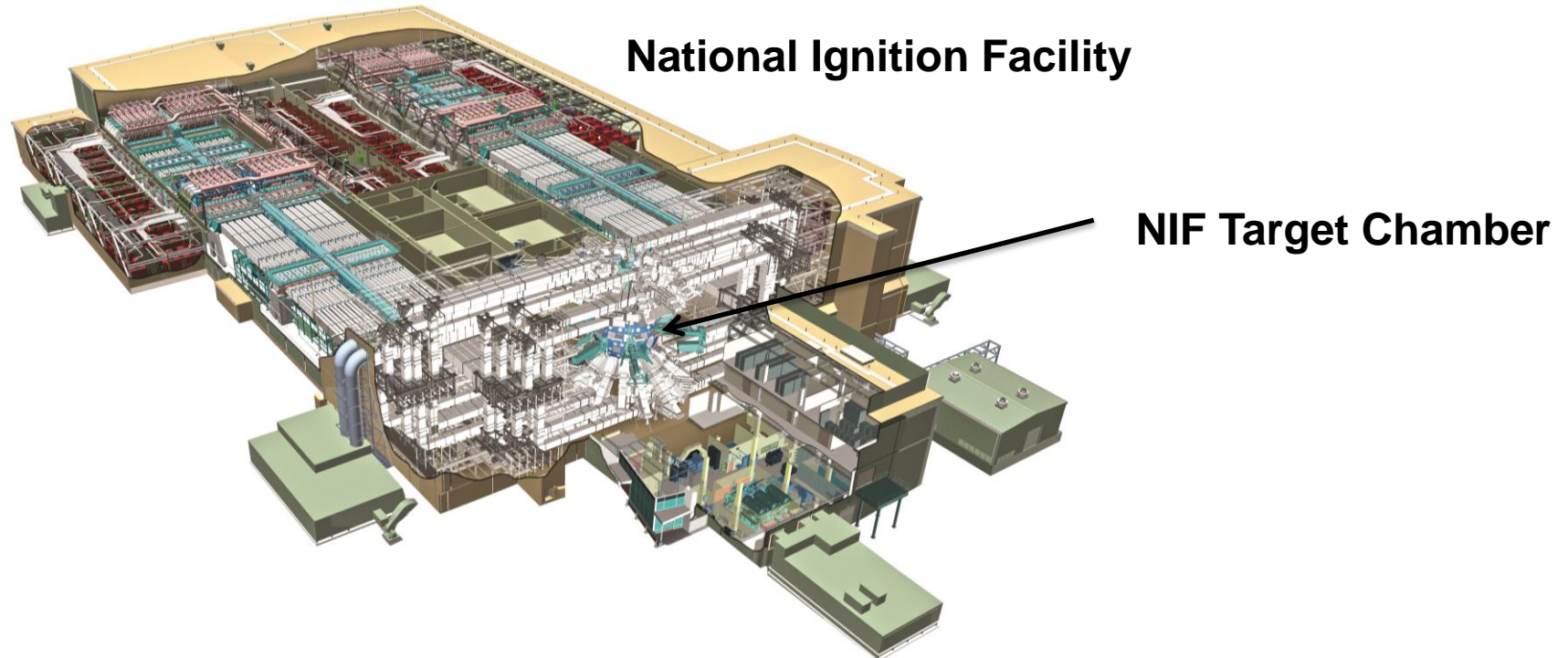
# **Evaluating radiation-induced noise effects on pixelated sensors for the National Ignition Facility**

**SPIE 2013**

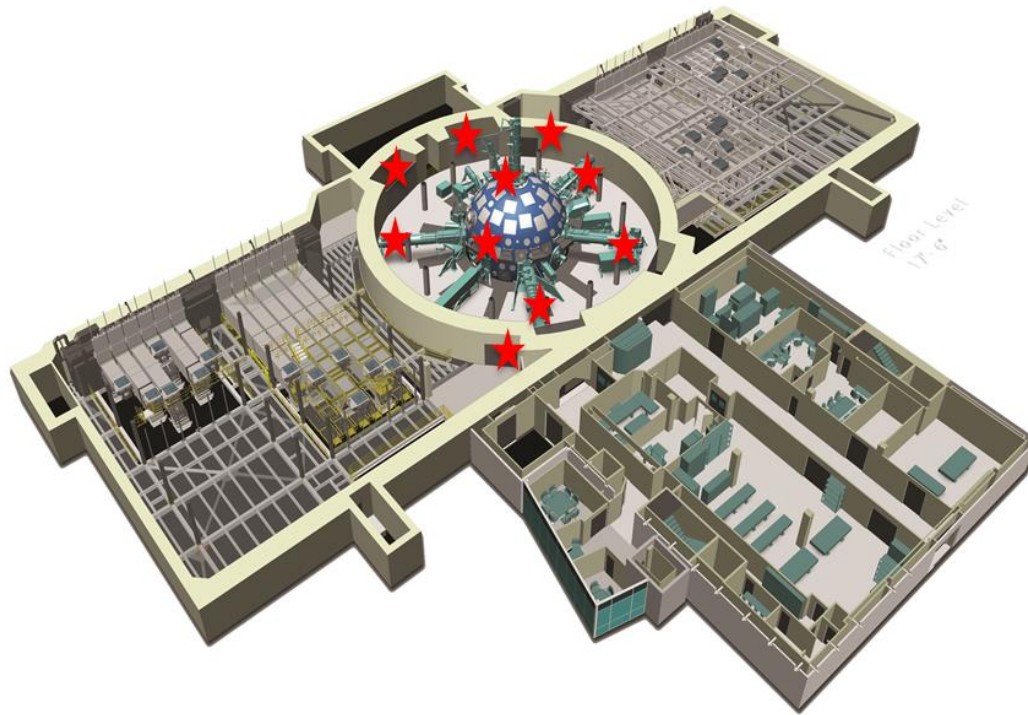
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## National Ignition Facility (NIF)

- The National Ignition Facility (NIF) is a 192 beam laser facility designed to support the Inertial Confinement Fusion (ICF) program.
- The facility was designed to have the capability of producing a deuterium-tritium (D-T) target shot in excess of 20 MJ of energy or  $7.1 \times 10^{18}$  neutrons at 14 MeV.
- A (D-T) target shot will generate 14 MeV neutrons at Target Chamber Center that propagate through the chamber into the Target Bay with multiple scatters, resulting in a high fluence, broad energy band of neutrons.



# The NIF radiation will potentially damage many alignment and diagnostic cameras

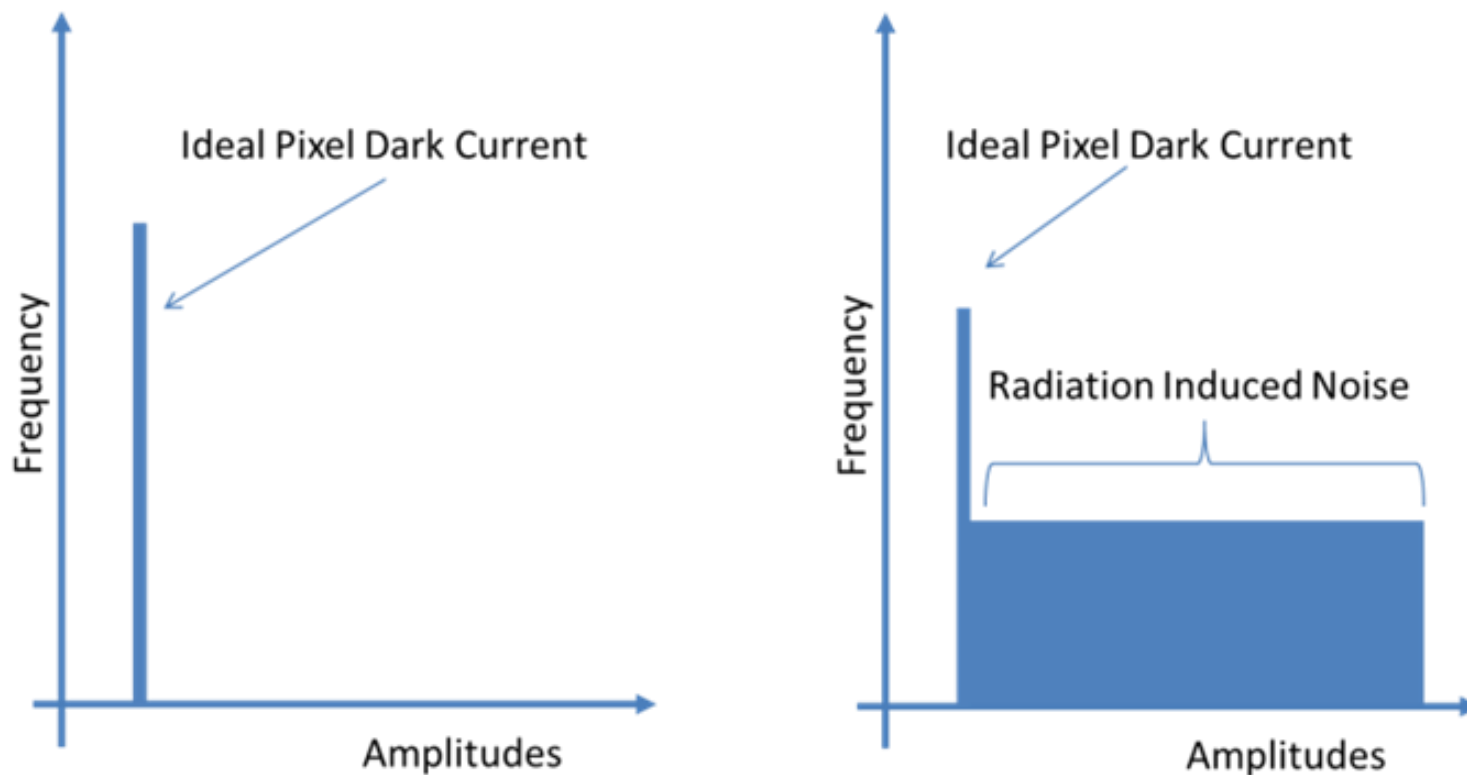


- Sectional view of the target bay at the equator

- Camera systems exist on all levels of NIF
- Facility System Include:
  - Target Alignment Sensor (TAS)
  - Chamber Center Reference System (CCRS)
  - Chamber Interior Viewing System (CIVS)
  - Final Optics Damage Inspection System (FODI)
- Diagnostics System Include:
  - VISAR, Backscatter (FABS & NBI), SXI, Gated Imagers, other

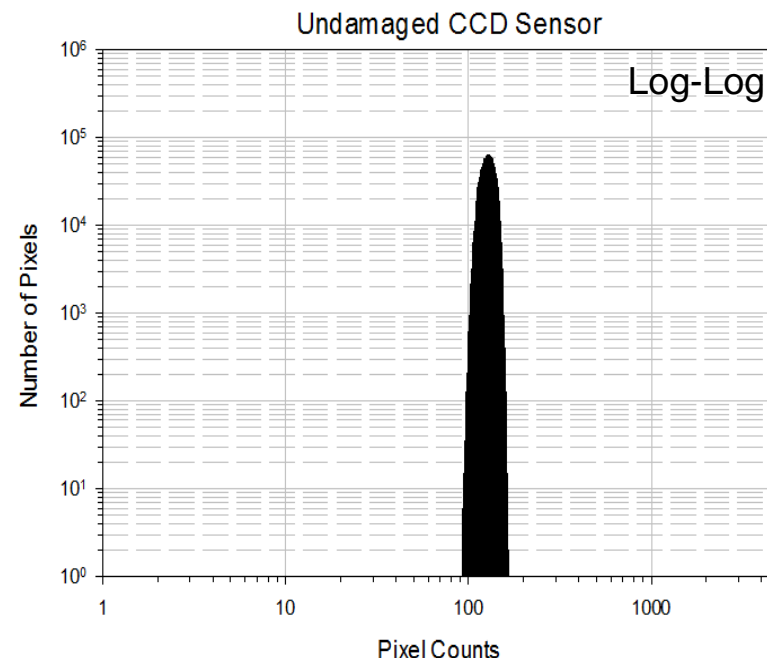
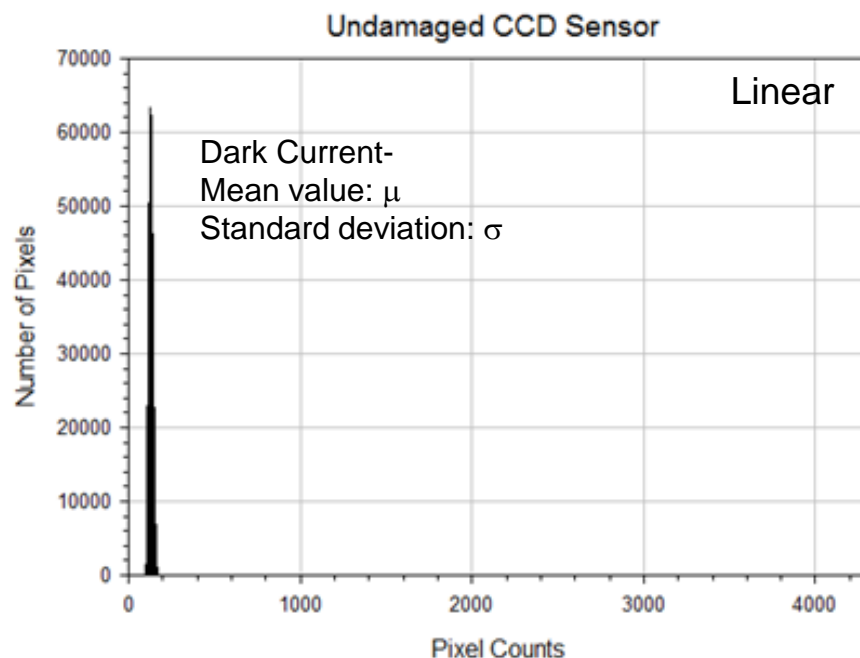
NIF has a variety of systems that have a 8, 10, 12, or 16 bit CCD/CMOS based imagers as part of their data collection. These cameras are exposed to 14MeV neutrons during a yield shot. In this presentation we develop a new method to evaluate camera system exposed to neutrons.

## Monitoring the health of a pixelated sensor



Observation of a sensor pixel damage is usually observed through a simple Histogram that represents all the possible pixel counts.

## Histogram of undamaged sensor

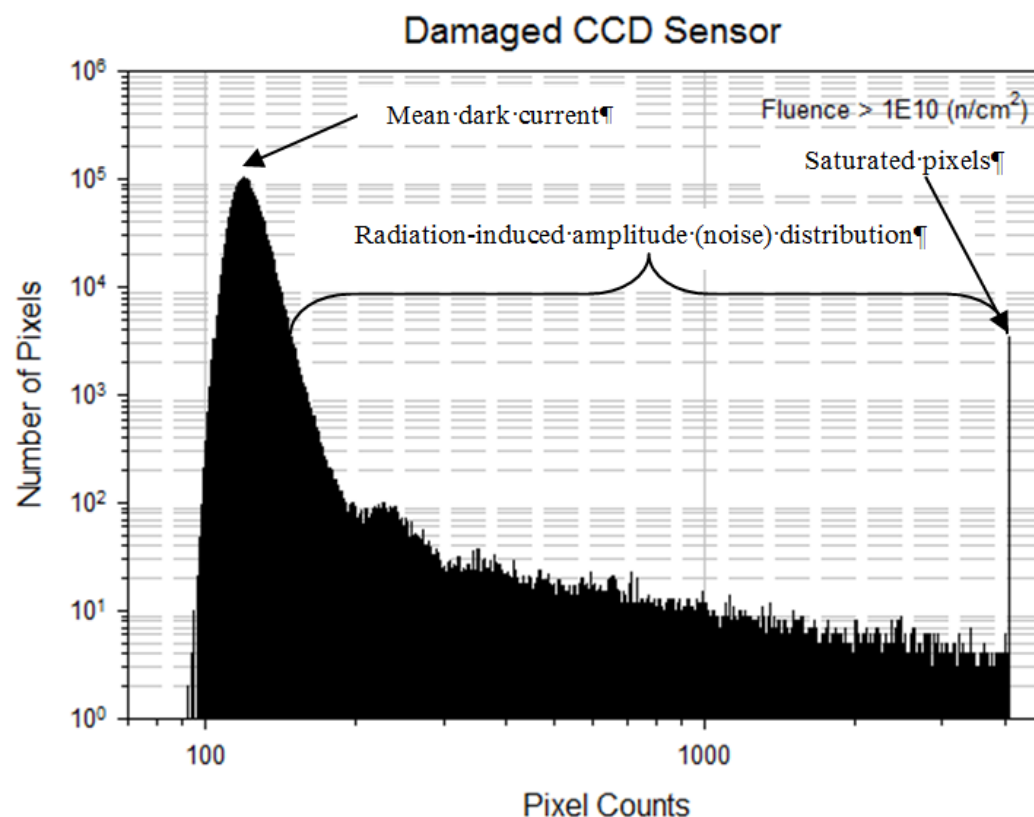


$$f_{Gauss}(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- A histogram representation of an undamaged 12 bit CCD sensor dark field image where the horizontal axis represents the pixel intensity values in counts. The same data is displayed in each graph; however the plot on the right is shown in log-log space.

**For an undamaged sensor the dark current can be represented by a Gaussian function. The mean value of the dark current is  $\mu$ , with standard deviation  $\sigma$ .**

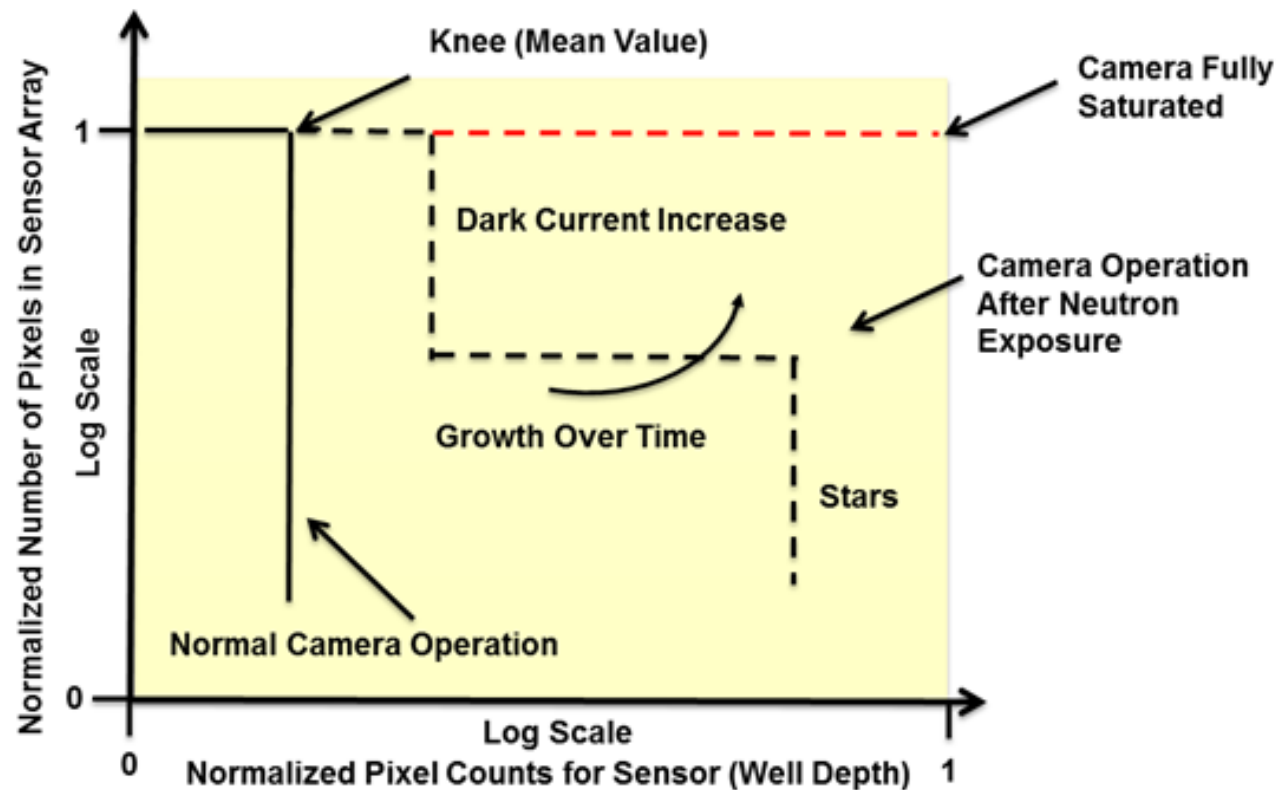
# Histogram of a 12 bit sensor exposed to 14 MeV neutrons with a cumulative fluence of $> 1\text{E}10 \text{ n/cm}^2$



A histogram of a 12 bit CCD sensor exposed to a cumulative fluence of greater than  $1 \times 10^{10}$  14MeV neutrons/cm<sup>2</sup>. The mean pixel dark current is still observed at the left end of the distribution with the additional amplitudes representing radiation damaged pixels extending to the maximum (saturated) count of 4095.

**A sensor exposed to 14 MeV neutrons exhibits short and long term damage that is manifested by “Stars”, low charge transfer efficiency, and increased dark current.**

## Advantages to viewing the health of a sensor differently



A normalized reverse sum histogram plot is developed to provide concise information as to the health of the sensor. Plot also leads to a analytical way of predicting future damage as a function of yield.

## Gaussian function and the normalized reverse sum histogram.

The reverse sum histogram for a Gaussian distribution is:

$$RSH_{Gauss}(x; \mu, \sigma) = 1 - \Phi(x; \mu, \sigma)$$

where  $\Phi(x; \mu, \sigma)$  is the cumulative probability distribution function for a Gaussian equation

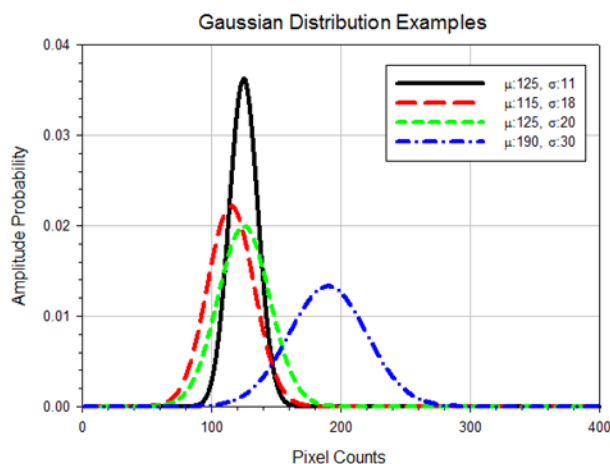
$$\Phi(x; \mu, \sigma) = \int_{-\infty}^x f_{Gauss}(x'; \mu, \sigma) dx' = \frac{1}{2} \left[ 1 + \operatorname{erf} \left( \frac{x - \mu}{\sqrt{2\sigma^2}} \right) \right]$$

The error function above is given by the following equation

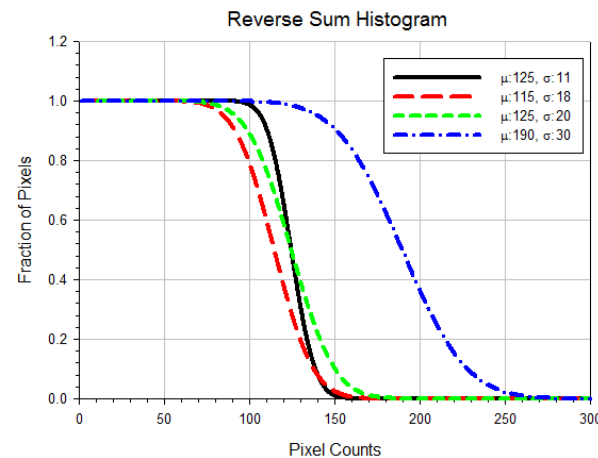
$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$$

**Gaussian function represents undamaged pixel dark current. A reverse sum histogram for this function can be described as the Error function.**

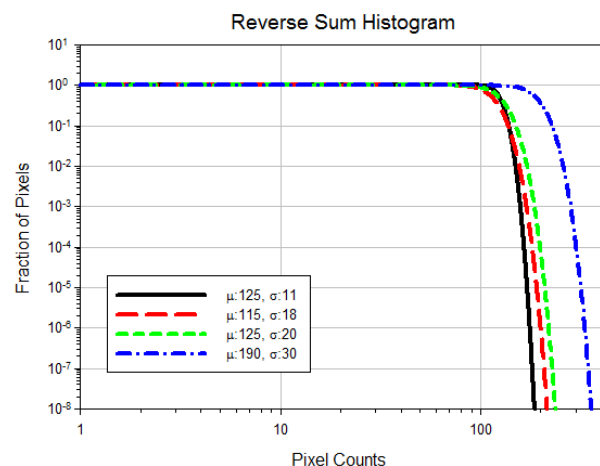
## Example of Gaussian distributions for undamaged pixels



A



B



C

- A: Gaussian probability distribution functions which represent the dark current in undamaged CCD pixels
- B: normalized reverse sum histograms on linear plot
- C: normalized reverse sum histograms on a log-log plot

**Example Gaussian probability and the associated normalized reverse sum histograms for undamaged pixels representing the sensor dark current. The mean and standard deviation are chosen to describe a typical undamaged sensor.**

# Equations describing a damage curve after being exposed to neutrons

- To properly describe the dark current of the sensor after the sensor is exposed to neutrons, a Exponential function convolved with a Gaussian is required. This function then describes
  - The number of pixels that are exponentially decaying with increasing dark current values.
  - The mean dark current that describes the undamaged pixel population.

Ex-Gauss function is described as:

$$f_{ExGauss}(x; \mu, \sigma, \tau) = \frac{1}{2\tau} \left[ e^{\left(-\frac{x}{\tau} + \frac{\mu}{\tau} + \frac{\sigma^2}{2\tau^2}\right)} \right] \left[ 1 + \operatorname{erf}\left(\frac{-\sigma^2 + x\tau - \mu\tau}{\sqrt{2}\sigma\tau}\right) \right]$$

$x$ - represent the dark current amplitude

$\mu$ - mean dark current

$\sigma$ - standard deviation of the Gaussian

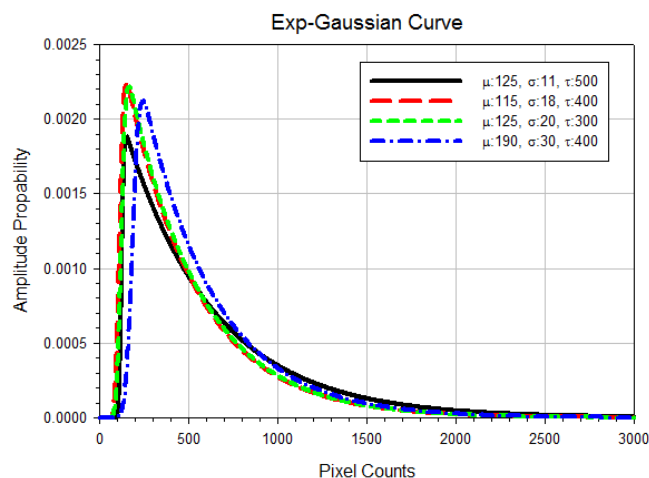
$\tau$  – is the exponential decay coefficient

The reverse sum histogram for the Ex-Gauss is:

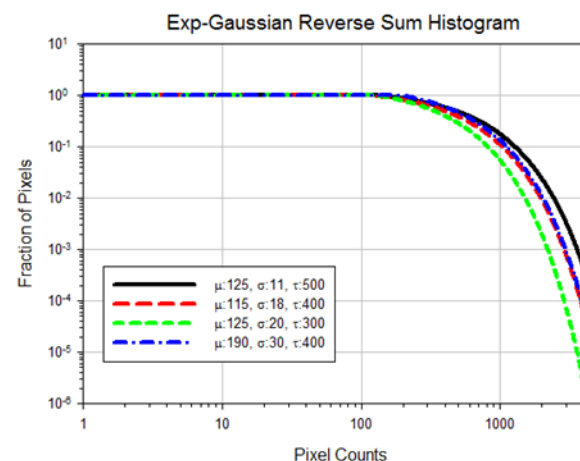
$$RSH_{Exp-Gauss}(x; \mu, \sigma, \tau) = 1 - \Phi(u; 0, v) + e^{-u+v^2/2+\ln(\Phi(u;v^2,v))}$$

Where  $u = (x-\mu)/\tau$ ,  $v = \sigma/\tau$  and  $\Phi(x;\mu,\sigma)$  is the cumulative probability for a Gaussian discussed earlier

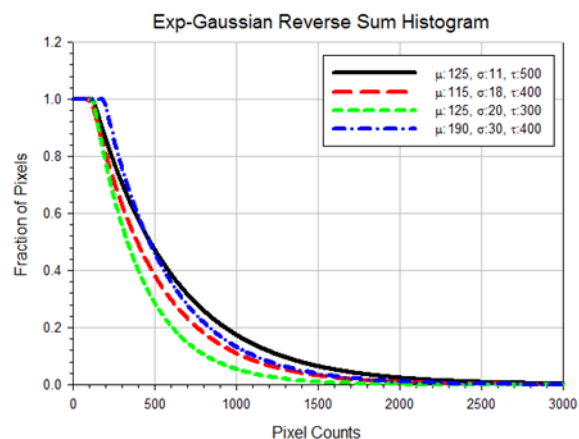
## Example of Ex-Gauss distributions for damaged pixels



A



B



C

- A: An exponentially modified Gaussian probability distribution function representing sensors with damaged pixels
- (B, C) are normalized reverse sum histograms for this function.
- The sample values chosen for the mean, standard deviation and exponential decay are typical of those found describing the damaged pixels for our CCDs.

## Parameters describing sensor pixel damage based on reverse sum histogram

- The total probability distribution function is the sum of the Gaussian and exponentially-modified Gaussian functions for the observed statistics. Each function separately describes the undamaged and damaged pixels.
- A weighting factor ( $0 \leq a \leq 1$ ) changes that fraction of pixels that follow each distribution, so the net probability distribution function can be described by the following equation:

$$f_{Total}(x; \mu, \sigma, \tau, a) = af_{Gauss}(x; \mu, \sigma) + (1 - a)f_{ExpGauss}(x; \mu, \sigma, \tau)$$

- The four parameters ( $\mu, \sigma, \tau, a$ ) represent the pixel parameters of the graph in relation to well depth capacity and pixel damage population in relation to neutron yield.

The reverse sum histogram for this function is then:

$$RSH_{Total}(x; \mu, \sigma, \tau, a) = aRSH_{Gauss}(x; \mu, \sigma) + (1 - a)RSH_{Exp-Gauss}(x; \mu, \sigma, \tau)$$

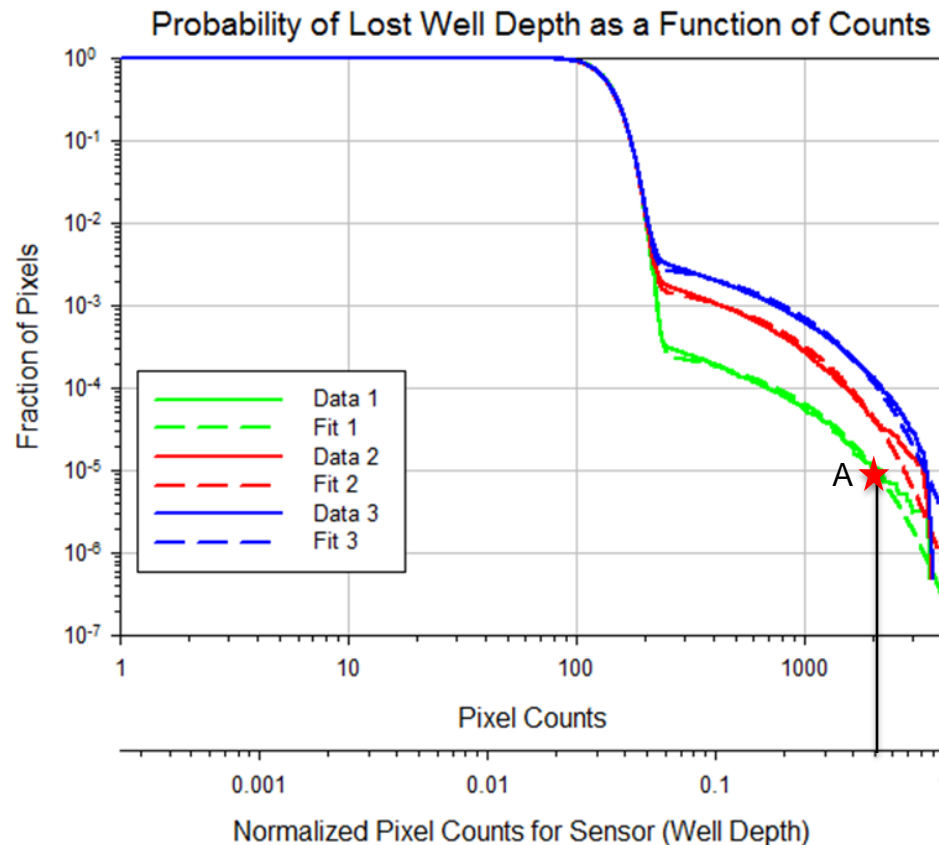
# Plot describing probability of lost well depth as a function of counts for different cumulative yields

Fit values are:  $(\mu, \sigma, \tau, a) =$

1- (138.4, 28.1, 567.9, 0.99971)

2- (137.8, 28.2, 506.4, 0.99822)

3- (138.1, 28.2, 565.7, 0.99674)



Cumulative Yields

Data 1 - Yield: 1.1E15

Data 2 - Yield: 4.3E15

Data 3 - Yield: 7.6E15

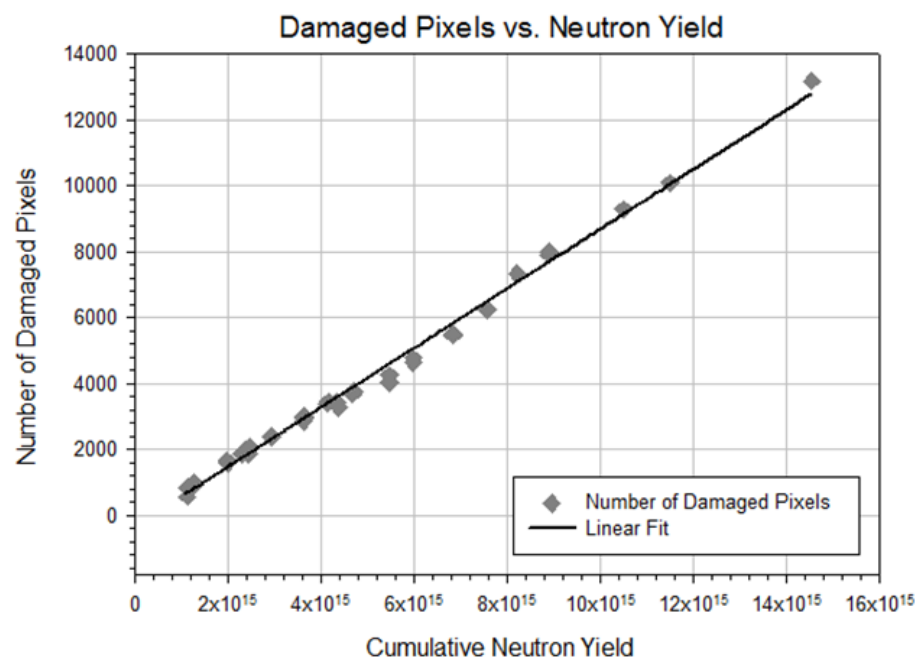
Reverse sum histogram data with best fit curves for three images taken after increasing yields. Point "A" represents at least 50% of the well depth is occupied for 0.001% of the pixels.

# Plot to predict the sensor pixel damage as a function of neutron yield

- With the best fit parameters ( $\mu, \sigma, \tau, a$ ) known, the forth parameter “a”, which describes the weighting between undamaged and damaged pixels has a linear dependence on yield.
- This parameter “a” can be used to describe the number of damaged pixels by the equation:

$$n_{damaged}(a) = n_{total}(1 - a)$$

- A plot can be generated describing the linear representation of damaged pixels vr shot yield



The plot of damaged pixels as a function of yield can now be used to predict future camera damage. For this camera, the slope is 90.8 damaged pixels per 1E14, 14 MeV neutron yield.

# Summary

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- We have described a series of algorithms for a two dimensional representation of graphic data that allow for the succinct visual evaluation of an image sensor performance when exposed to a neutron radiation field.
- Several figures-of-merit can be easily track over time leading to a quantitative relationship between exposure to radiation damage and the performance of the imaging sensor array.
- Also we have implemented a novel technique that allows for the prediction of future image sensor performance based on the response function of existing radiation exposures.
- Information that can be extracted from the plot include but not limited to dark current and well depth values based on pixel population, charge transfer efficiency failures, and radiation damage performance effects over time.

NIF

